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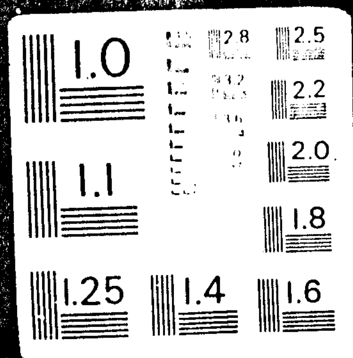

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The 1965 ARPA-AEC Joint Lightning Study at Los Alamos*

Volume IV

Discrimination against False Triggering of
Air-Fluorescence Detection Systems
by Lightning

by

Guy E. Barasch

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VOLUME IV*

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LA-3754 Volume I. T. Robert Connor, "The Lightning Spectrum. Charge Transfer in Lightning. Efficiency of Conversion of Electrical Energy into Visible Radiation." Issued December 1967.

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THE 1965 ARPA-AEC JOINT LIGHTNING STUDY AT LOS ALAMOS

VOLUME IV

DISCRIMINATION AGAINST FALSE TRIGGERING OF

AIR-FLUORESCENCE DETECTION SYSTEMS BY LIGHTNING

Guy E. Barasch

ABSTRACT

Optical discrimination techniques to prevent false triggering of nuclear-explosion-excited air-fluorescence detection systems by lightning are evaluated. The spectra of lightning and of air fluorescence are very different: lightning emits a strong continuum and neutral and ionized atomic line radiations, whereas the air-fluorescence spectrum is primarily molecular band radiation. The discrimination technique makes optimum use of two detectors to identify the source of a light pulse through these differences. False triggering of the detection system occurs either when the source is misidentified or when one of the measurements cannot be made because the incident signal at that wavelength is below the detection threshold. The present evaluation is a statistical prediction of false-triggering rates taking into account: lightning emissions, air-fluorescence emissions, atmospheric propagation mechanisms, detector-component parameters, and background radiation.

Two detection-system designs are evaluated, each of which specifies a narrow passband at 3914 Å for detection of N_2^+ 1N (0,0) fluorescence. One uses 2-in.-diam "LASL-2" all-sky radiometers; the other uses improved 5-in.-diam "LASL-5" all-sky radiometers. Four discrimination-channel wavelengths are evaluated: 4140 Å (40-Å bandwidth), 4950 Å (220-Å bandwidth), 5000 Å (20-Å bandwidth), and 6563 Å (20-Å bandwidth).

The predicted yearly false-triggering rates at a typical site are:

	Discrimination Wavelength			
	4140 Å	4950 Å	5000 Å	6563 Å
Two-inch radiometers	1180	~ 6	< 420	710
Five-inch radiometers	660	0.2	< 136	510

The best discrimination capability is realized with the 4950-Å, 220-Å-bandwidth channel, because the 3914-Å/4950-Å radiated spectral-intensity ratios of lightning and air fluorescence are substantially different, and because lightning radiates more flux in the 220-Å band near 4950 Å than in any of the other bands considered. The rates of source misidentifications and below-threshold false triggers are therefore minimized. Owing to the superior discrimination characteristics of the 4950-Å channel in conjunction with 5-in. radiometers, we recommend this combination for improvement of current detection systems or use in any new system designs.

I. INTRODUCTION

This report is the fourth of a series on the optical results of the 1965 lightning study. The physics of the optical outputs of lightning and their detection has been presented in the first three volumes.[1-3] In this report, optical discrimination against lightning-produced light pulses by nuclear-explosion-excited air-fluorescence detection systems is analyzed and evaluated.

Detection of nuclear explosions high in the atmosphere or in interplanetary space can be accomplished by detecting optical fluorescence of air, in the upper atmosphere, excited by x rays from the explosions. The energy radiated by the fluorescence is on the order of a few percent of the incident x-ray energy and is concentrated primarily in narrow molecular bands of N_2 and N_2^+ throughout the visible and near-visible spectrum. This detection method has an inherently high sensitivity even during daylight, when background light levels are high: typical, practical systems, such as the Los Alamos Air-Fluorescence Detection System designed in 1959 by Westervelt and Hoerlin,[4] can detect, in daylight, a 1-kt nuclear explosion up to at least 50,000 km above the atmosphere. The maximum detection range increases by about a factor of 30 at night.

Distinguishing between light pulses from lightning flashes and nuclear-explosion-excited air fluorescence* is a necessary feature of an effective detection system. Lightning storms emit many strong optical signals and can be arbitrarily close to a ground-based detection station. The frequency at which these false pulses are detected can effectively negate the capability to detect and identify a "real" nuclear-explosion produced signal.

This problem was recognized in the early detection-system design stages. Consequently, two techniques were proposed by which inherent differences of the optical signals of lightning and air fluorescence might be used to recognize automatically the source type and so "discriminate" against false alarms produced by lightning. The study and evaluation of these and other techniques to prevent or limit lightning-produced false alarms has been given the title "lightning discrimination."

One of the proposed discrimination techniques was based on possible differences in the optical pulse shapes of lightning and air fluorescence. The expected pulse characteristics for air fluorescence had been determined theoretically (and were later substantiated experimentally). However, in an early lightning study in 1959, we were able to show that discrimination based exclusively on pulse shape is not practical, because many lightning pulses have shapes identical to air fluorescence.

The second proposed discrimination technique was based on differences between the optical spectra emitted by lightning and air fluorescence.[4,5] The lightning spectrum was not known quantitatively; however, it was known qualitatively that, in contrast to the continuum-free molecular band radiation of air fluorescence, lightning radiates a strong continuum, as well as atomic-line and, perhaps, molecular-band features. A system of detectors with narrow bandwidths at two or more spectral regions might be able to sense these differences and so determine the source of the detected pulse.

Studies of an air-fluorescence spectrum and an estimated lightning spectrum led to the choice of a 20-Å wide band at 3914 Å for detection of the air-fluorescence (0,0) radiation of N_2^+ 1N, and a 20-Å wide band at 4140 Å, which is very weak in air fluorescence but is in the strong continuum of lightning, for lightning discrimination. Both sources produce strong signals at 3914 Å, but lightning signals are much stronger at 4140 Å, relative to 3914 Å, than air-fluorescence signals. The signal ratio, 3914-Å/4140-Å, could then be used to identify the source type.

A lightning study was conducted in 1963 at Los Alamos by R. A. Amato and other EG&G personnel to evaluate the Los Alamos Air-Fluorescence Detection System and lightning discrimination based on source spectra. Amato concluded that the 3914-Å/4140-Å ratio of detected signals was an effective discrimination parameter for 98% of the detected lightning pulses, and he recommended the construction of an automatic lightning-discrimination system.[6]

However, there were four shortcomings of the

*For brevity, we will shorten this term to "air fluorescence" for this volume; and for clarity we will therefore not refer to lightning radiation as "fluorescence."

early lightning studies:

1. The conclusions were based more on a statistical treatment of the data than on a physical understanding of the emission and signal-propagation processes.

2. The conclusions were applicable to the detectors that had actually been operated, but they were not extended to newer detector designs.

3. Newly-proposed spectral regions for discrimination had not been studied.[5]

4. The operation of a lightning-discrimination system had not been analyzed fully. For example, the conditions that would produce a false alarm were not defined, and, in fact, one important source of false alarms was totally ignored.

In the present analysis we depart from earlier ones: we consider in greater detail the emission, propagation, and detection of lightning and air-fluorescence radiations, and we define the conditions that can lead to false alarms. For example, we distinguish between genuine false alarms, where the recorded signals actually indicate on close inspection that an air-fluorescence pulse was detected, vs the times when the automatic discrimination equipment is "fooled" and so permits a lightning signal to be recorded ("false trigger"). When the results of these considerations are incorporated into an evaluation of lightning discrimination, the shortcomings of the earlier analyses are remedied.

For optimum lightning discrimination, we find that large amounts of light must be detected from lightning. This requirement ensures that weak lightning pulses are detected and properly measured, so that they can be accurately identified as lightning and so do not produce false triggering. The best way to detect large amounts of lightning radiation is to use a broad spectral bandwidth sensitive to the strong continuum of lightning. A 220-Å wide region centered at 4950 Å is shown to be optimum for lightning discrimination of a 3914-Å detection system, based on (a) the collection of a large amount of the lightning continuum, and (b) the fact that the air-fluorescence spectrum is very weak in this region, relative to 3914 Å.

The quantitative conclusions presented in this report are based on considerations of the following aspects of lightning, the atmosphere, and discrimination systems:

1. The lightning spectrum and its variations.

2. Modifications of the spectrum during propagation to the detector.

3. The spectra of nuclear-explosion-excited air fluorescence.

4. Detector sensitivities, fields of view, and bandwidths.

5. The ways in which false triggering occurs.

Volumes I to III[1-3] deal with the input data represented above by Items 1 and 2. Items 3 through 5 are treated in this volume in the following sequence:

1. Section II discusses system operation, with emphasis on how false triggering is produced.

2. Section III presents the spectra of nuclear-explosion-excited air fluorescence, as well as a typical lightning spectrum, and enumerates the spectral regions that appear practical for discrimination.

3. Section IV uses parameters of the detectors to calculate their sensitivities at the spectral regions of interest.

These input data are followed, in Section V, by a derivation of anticipated false triggering rates when the various spectral regions are used for discrimination. These results are used to formulate the recommended design for discrimination against lightning by modern detection systems.

II. OPERATION OF THE LIGHTNING-DISCRIMINATING DETECTION SYSTEM

The detection systems for which these evaluations are valid use a continuously-operated radiometer* sensitive to a wavelength region in which

*In previous volumes of this report,[2,3] and in another related report,[7] we have used the term "photometer" to mean what we now call a "radiometer." We make this change in deference to the Nomenclature Committee of the Optical Society of America, which has recently endorsed the restriction of the term "photometer" to devices for measurements of quantities only to the extent that they are visible to the human eye.[8]

nuclear-explosion-excited air fluorescence is strong. Regions which have been proposed for nuclear-explosion detection are: 3914 Å, 20-Å-wide [N_2^+ 1N (0,0)]; 4278 Å, 20-Å-wide [N_2^+ 1N (1,0)]; and a band within the near infrared, extending from ~ 6000 to ~ 11,000 Å [N_2 1P group]. The detection systems are limited in sensitivity at a particular spectral region by statistical noise of the photoelectron beam of the detector. This noise is generated in daylight by the detection of the background light, and at night both by detection of background light and the internal processes of the detector, such as dark current. Typical daylight sensitivities of the detection systems, expressed in terms of the distance from which an explosion can be detected, range from $5.5 \times 10^4 \sqrt{Y_x}$ km, where Y_x is the x-ray yield of the explosion in kilotons, for the LAAFDS[4] as designed in 1959, to an estimated $10^6 \sqrt{Y_x}$ km for the newest design. The sensitivities are 10 times or more greater at night than in daylight.

Lightning typically produces detectable signals from distances of 60 km during daylight and of more than 100 km at night. The actual maximum distance from which lightning can be detected depends on atmospheric conditions, local environment, the lightning storm itself, and details of detector construction, such as field of view. If storms occur closer than the maximum-detection distance, lightning can trigger any of these detectors at a high rate, so that it becomes impossible to isolate a nuclear-explosion-produced signal.

To decrease the rate at which triggering is produced by lightning, inherent differences between lightning signals and air-fluorescence signals can be used to differentiate between them. Such differences can occur in the pulse shape, the shape of the optical spectrum, the characteristics of the electromagnetic radiations, or the relationship between optical and electromagnetic radiations. In the preliminary optical lightning study, in 1959, we found that differences in optical pulse shapes are not sufficient for useful differentiation of all lightning pulses.

The spectra of lightning and air fluorescence, however, are basically very different: lightning emits a strong continuum, and neutral and ionized atomic line radiations, whereas the air-fluorescence spectrum is composed primarily of molecular band radiations. Because of these differences, spectral regions exist in which the emitted intensities can be used to identify the source. We will present the actual spectra of lightning and air fluorescence, and derive such spectral regions from them, in Section III, after presenting the criteria by which optimum spectral regions must be chosen.

To effect discrimination on the basis of differences in source spectra, two regions of the detected spectrum are measured. One region contains the spectral feature used for air-fluorescence detection and is called the detection channel. The other region is called the discrimination channel. The two spectral regions are chosen so that their relative signals for air fluorescence differ in a known way from the signals for lightning. Any detected signals in the two regions are automatically compared, and the type of source is identified on the basis of the comparison.

As an example, suppose we are using a detection channel at 3914 Å and a discrimination channel at 4140 Å. The signal ratio 3914-Å/4140-Å for most air-fluorescence spectra is known to be > 10; whereas that for lightning averages ~ 1 and is never larger than 6. We therefore choose a discrimination-ratio criterion of 10; that is, we set our apparatus so that all pulses with a 3914-Å/4140-Å ratio < 10 are rejected. In this way, we reject all lightning-produced signals for which the discrimination-ratio test is possible.

The discrimination-ratio test becomes impossible for pulses so small that, although detected in the detection channel, they are below threshold in the discrimination channel. For a given discrimination channel, no solution to this kind of false triggering can be effected while full detection sensitivity is maintained. The number of such pulses that occur, however, depends on the spectral region chosen for discrimination, and much of our evaluation has been concerned with minimizing these "below-threshold" false triggers.

As an example of below-threshold false triggering, consider again a detection system with channels at 3914 and 4140 Å. Suppose a lightning pulse produces signals at the detectors with a 3914-Å/4140-Å ratio of 2.0, well within the range of lightning-produced ratios.[2] A pulse with this ratio would be rejected by the discrimination system if it could be detected in both channels. Suppose, however, that the pulse is only slightly above the detection threshold at 3914 Å. Because 3914- and 4140-Å channels have about equal sensitivity, and because we have postulated a 4140-Å signal only half as large as the threshold 3914-Å signal, the 4140-Å signal is smaller than the discrimination-channel threshold and thus cannot be detected. A false trigger is produced, even though the spectrum emitted by this pulse is inherently suitable for discrimination. This is the major source of false triggering mentioned in Section I as not having been noted in previous lightning-study analyses.

In the examples given above, we have assumed that lightning and air-fluorescence have detection-channel to discrimination-channel ratios different enough to permit unambiguous source determination. This assumption was manifest in our statement that the 3914-Å/4140-Å ratio was > 10 for air fluorescence, and < 6 for lightning. There are a number of spectral regions suitable for unambiguous differentiation between lightning and a typical air-fluorescence spectrum. However, in some of these spectral regions, an unambiguous determination of source type becomes impossible if we consider typical nuclear-explosion-excited air-fluorescence spectra. This ambiguity is an indirect cause of detection-system false triggering.

Suppose, with the detection system discussed above, we must consider an air-fluorescence spectrum excited by a high-altitude nuclear explosion in which the 3914-Å/4140-Å ratio is only 5. Such a ratio may be possible when high-yield explosions occur near the atmosphere, owing to a decrease of the 3914-Å feature relative to the rest of the spectrum. We must set the discrimination-ratio criterion to a value less than 5, say 4, to be sure to detect and not reject a pulse from this source. However, there are also lightning pulses with ratios greater than 4. When these pulses are detected, they are misidentified as air fluorescence and so produce "source-misidentification" false triggers.

Thus, there are two inherent lightning-caused sources of false triggering of a nuclear-explosion detection system: source misidentification, and below-threshold pulses incident on the discrimination-channel radiometer. This false triggering can be minimized or eliminated by the proper choice of discrimination wavelength.

First, source misidentifications can be minimized if a discrimination channel can be found for which the range of detection channel to discrimination channel spectral-irradiance ratios produced by air fluorescence and the range of ratios produced by lightning overlap the least.

Second, below-threshold false triggering can be minimized if the sensitivity to lightning of the discrimination channel radiometer is made as large as possible relative to the detection channel sensitivity. We have noted that many lightning pulses which produce just-detectable signals in the detection channel would produce below-threshold signals in a normal-sensitivity discrimination channel. Any enhanced sensitivity of the discrimination channel to lightning would permit much false triggering to be eliminated.

Radiometer sensitivity to lightning can be increased by: 1) use of a larger radiometer, 2) a more sensitive detection element, or 3) detection of more of the emitted lightning radiation. The first two methods do not effectively increase the discrimination-channel sensitivity relative to that of the detection channel for the following reason. Whatever changes are applied to the discrimination channel also will be applied to the detection channel to increase <u>its</u> sensitivity, and there will be no change of <u>relative</u> sensitivity.

However, the third approach can be made so that the changes are not applicable to the detection channel radiometer. A spectral region for discrimination must be found which meets two criteria:

1. lightning radiates strongly relative to the detection channel, and

2. nuclear-explosion air fluorescence radiates weakly enough, relative to the detection channel, that the source can be recognized from the ratio of the two channels' outputs.

One discrimination region that meets these criteria is a narrow passband that surrounds a bright atomic-line emission of lightning, but which is a relatively dark region of the air-fluorescence spectrum. Here the sensitivity increase for lightning detection occurs because the atomic-line radiation in the discrimination channel is larger than the continuum radiation in the detection channel.

Another suitable spectral region is a broad region of continuum radiation. Lightning exhibits a strong continuum, at least below 6000 Å, and broad spectral regions can be found in which lightning radiates much more strongly, relative to 3914 or 4278 Å, than nuclear-explosion-excited air fluorescence. In this case, the sensitivity advantage occurs as follows. Owing to its strong continuum, lightning radiates much more flux in a broad spectral region at the discrimination wavelength than it does in the narrow detection channel. Between 3900 and 6000 Å, the flux radiated by lightning is approximately proportional to the bandwidth; and, so, a 220-Å-wide discrimination channel detects about 11 times as much flux as does a 20-Å-wide detection channel. The background-radiation induced noise is also larger in the discrimination channel, but only by a factor proportional to the square root of the bandwidth. Thus, a net gain of signal-to-noise ratio, or sensitivity, is realized for lightning.

III. SPECTRAL REGIONS FOR DISCRIMINATION

We have shown that the following criteria must be satisfied for effective discrimination.

1. The ratio of expected air-fluorescence signals in the detection and discrimination channels must be as different as possible from the ratio for lightning, and, in particular, the overlap between the two ratio distributions must be minimal.

2. The signal-to-noise ratio of the discrimination channel under typical operating conditions must be as large as possible relative to that of the detection channel.

We must now find regions of lightning and air-fluorescence spectra that satisfy these criteria.

A. Spectra

A typical lightning spectrum recorded by Connor[1] and an air-fluorescence spectrum recorded in the laboratory by Hartman[8] are shown for comparison in Fig. 1. Both have 6- to 8-Å spectral resolution and were normalized to 3914 Å. The qualitative differences on which the lightning-discrimination technique is based are apparent: the predominant molecular-band features of air fluorescence vs the strong continuum and the neutral and ionized atomic-line features of lightning. The quantitative difference shown decreases with detection systems having poorer spectral resolution, owing to the decrease in peak intensities of the band features as they become effectively broader.

1. Lightning. The lightning spectrum of Fig. 1 is that of a subsequent return stroke 7 km from the spectrograph, corrected for atmospheric transmission. The collimated photoelectric data[2] have shown that most other lightning phenomena, such as cloud strokes and leaders, have similar spectra at 3914, 4140, and 6563 Å, although, as Connor also reported,[1] first-return-stroke spectra are somewhat different.

The spectrum shown is typical of subsequent-return-stroke spectra recorded at Los Alamos during the 1965 summer lightning season. Lightning occurring elsewhere or at other times of the year may differ in detail. However, the strong continuum and narrow atomic-line features are probably typical of most lightning strokes, and we infer that the visible spectra of all lightning phenomena excluding first return strokes are substantially the same as that shown in Fig. 1. The variations of this spectrum from pulse to pulse and its modification for the ~ 8% of all pulses that are first return strokes have been derived from the lightning-study data and are used in the discrimination-system evaluation.

2. Air Fluorescence. The air-fluorescence spectrum of Fig. 1 was excited by 800-eV electrons in air at a pressure of 0.07 Torr, corresponding to an atmospheric altitude of 66 km.[9] This altitude approximates the 60 km where the maximum x-ray energy would nominally be deposited from a high-altitude nuclear detonation. Therefore, the laboratory spectrum should closely approximate the spectrum of the air-fluorescence pulse produced by a high-altitude nuclear explosion, so long as the energy density deposited within the atmosphere is small, as would be true for the air-fluorescence pulse excited by a distant, exo-atmospheric nuclear explosion.

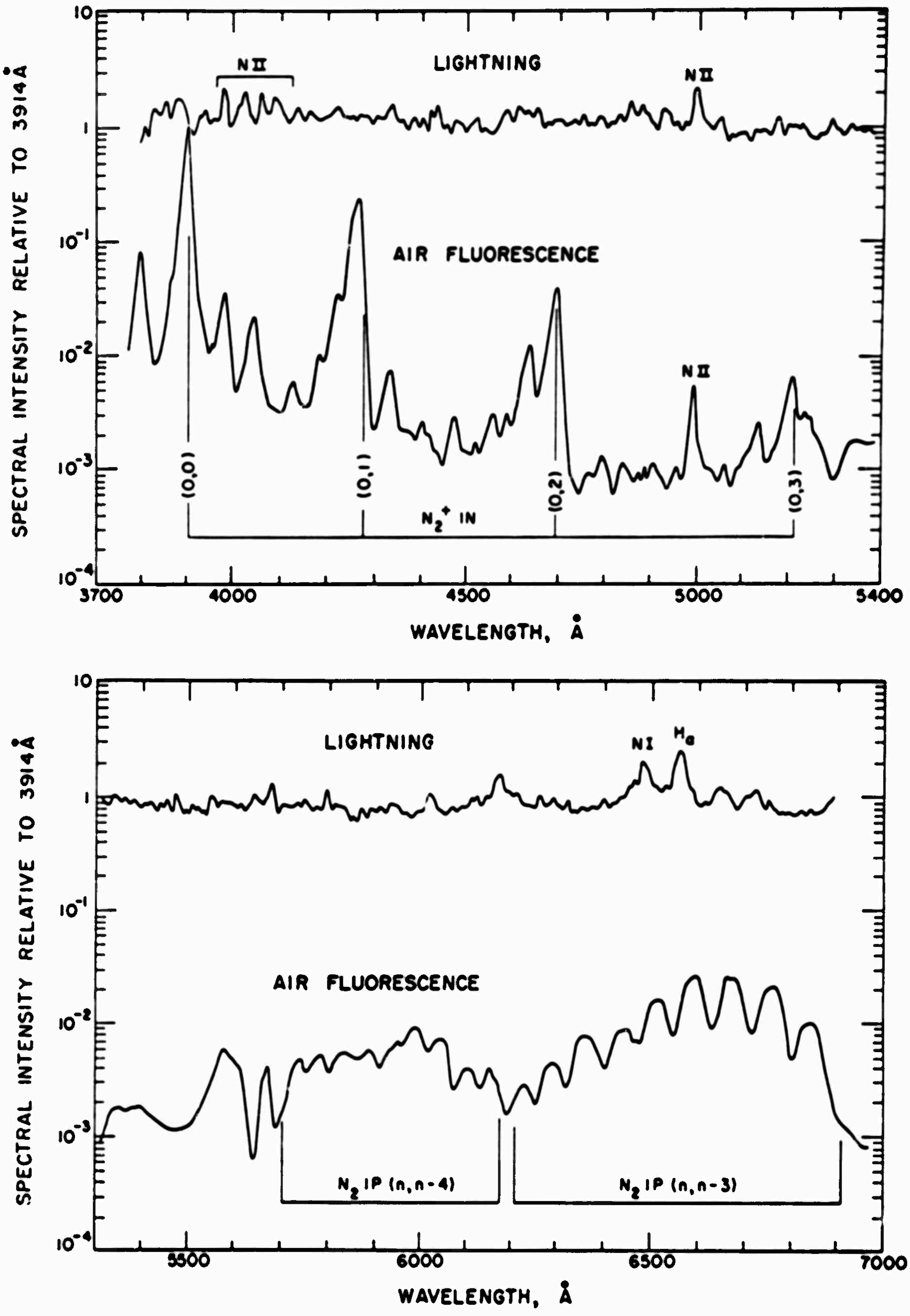


Fig. 1. Typical lightning and air-fluorescence spectra, relative to 3914 Å. Resolutions are 6 to 8 Å.

However, there are other cases of interest in which the air-fluorescence spectrum can differ substantially from the laboratory spectrum: 1) explosions within the atmosphere that produce fireball radiation, and 2) large explosions near the atmosphere that deposit large energy densities within it, such as the Starfish explosion.[10]

First, fireball radiation has a strong continuum very similar to that of lightning. Therefore, if fireball radiation is present, the discrimination system based on spectral differences between lightning and air fluorescence will not work. In this case, however, other parameters such as pulse duration can be used to discriminate against lightning.

Second, when a nuclear explosion occurs near the atmosphere, large densities of N_2^+ ions are produced in the atmospheric region where the x rays from the explosion are deposited. These ions appreciably trap their own radiation within the highly dosed volume by self-absorption, or resonance scattering, as described by Bennett.[11] Consequently, ground-based detectors see a decrease of 3914-Å [N_2^+ 1N (0,0)] radiation; the missing photons appear instead at 4278 Å (0,1), 4709 Å (0,2), or 5228 Å (0,3).

A system that uses 3914 Å for air-fluorescence detection and some other wavelength, such as 4140 Å, for lightning discrimination, will therefore see a smaller 3914-Å to 4140-Å ratio for a high dose-rate nuclear explosion than that predicted from the laboratory air-fluorescence spectrum. We have shown how this modification of the air-fluorescence spectrum can lead to higher false-triggering rates.

A system that used 4278 Å rather than 3914 Å for air-fluorescence detection would be three times less sensitive to weak pulses, but would not be adversely affected by spectrum modifications caused by self-absorption.

To evaluate lightning discrimination by systems designed to detect explosions near the atmosphere, we must know the fluorescence spectrum of highly dosed air. As representative examples, we have used spectra recorded from five high-altitude nuclear explosions, taken along lines of sight in which air-fluorescence radiation was predominant. The details of these spectra were obtained from unclassified sections of classified references, as follows:

1. Starfish. Spectrum recorded by Bennett[11] and reduced by Sappenfield.[12] A preliminary reduction of this spectrum is presented by Hoerlin in an unclassified report.[10]

2. Checkmate. Spectrum reported by Peek and Sappenfield.[13] No quantitative reduction is possible owing to the slitless operation of the spectrograph, but for the purposes of this report the spectrum appears qualitatively similar to the laboratory air-fluorescence spectrum of Fig. 1.

3. Kingfish. Two spectra along separate lines of sight reported by Peek and Sappenfield.[14]

4. Bluegill. Two spectra along separate lines of sight reported by Peek and Sappenfield.[15]

5. Teak. Spectrum reported by Stone.[16]

B. Discrimination Regions

On the basis of the lightning and air-fluorescence spectra of Fig. 1, a 3914-Å detection channel and any of four discrimination channels as listed in Table I appear practical for an effective detection and discrimination system. The 4140-Å discrimination region fits between the features, N_2 2P (0,3) and N_2^+ 1N (0,1) of the air-fluorescence spectrum; included within this passband is the weak N_2 2P (3,7). The 4950-Å discrimination region lies in a broad minimum of the air-fluorescence spectrum. It is limited at each end by strong features of N_2^+ 1N: the (0,2) transition below and the (0,3) above; the 220-Å bandwidth is the broadest passband that fits

Table I. Spectral Features of 3914-Å Detection Channel and Four Discrimination Channels

Wavelength Å	Bandwidth Å	Air Fluorescence	Lightning
3914	20	N_2^+ 1N (0,0)	C*
4140	40	N_2 2P (3,7)	C,NI(6),NI(10)
4950	220	N_2 2P (1,7) (4,1); NII	C,NII
5000	20	NII	NII
6563	20	N_2 1P (7,4)	Hα

*C = continuum

Table II. Detection-to-Discrimination Channel Ratios for Lightning and Air Fluorescence

	Spectral-Intensity Ratio (per Å)							
	3914 Å / 4140 Å		3914 Å / 4950 Å		3914 Å / 5000 Å		3914 Å / 6563 Å	
Source	20Å*	43Å*	20Å*	43Å*	20Å*	43Å*	20Å*	43Å*
Lightning								
Average	1.2	1.2	1.1	1.1	0.5	0.7	0.5	0.7
Maximum	~ 6.	~ 6.	~ 4.5	~ 4.5	~ 3.	~ 4.	~ 4.	~ 4.
Air fluorescence, derived from								
Laboratory	80.	43.	400.	220.	160.	160.	27.	14.
Checkmate (estimated)	> 10.	> 10.	> 10.	> 10.	> 10.	> 10.	> 10.	> 10.
Starfish	12.	7.	10.	7.0	3.	3.	0.7	0.4
Teak	6.0	3.0	7.	3.5	3.	3.	-	-
Kingfish								
(a)	5.0	3.0	8.5	4.8	-	-	20.	10.
(b)	4.0	2.4	7.5	4.3	7.	4.	11.	6.
Bluegill								
(a)	1.2	1.0	8.0	6.0	7.5	6.0	3.0	2.6
(b)	1.1	0.9	6.5	5.5	5.0	5.0	11.	10.

*3914-Å bandwidth

between these two spectral features and has an acceptably small response at both. The 5000- and 6563-Å discrimination regions are based on line features of the lightning spectrum. At 5000 Å, the fluorescence spectrum of Fig. 1 also shows an apparently strong line feature, with the same origin as that in lightning. However, in air fluorescence, this feature is much weaker than the 3914-Å detection feature. There is also moderately strong radiation at 6563 Å in air fluorescence due to the (7,4) band of N_2 1P, but in the spectrum of Fig. 1 it is weaker than 3914 Å.

The detection-channel to discrimination-channel ratios of spectral irradiances (W cm^{-2} Å^{-1}) that would be measured for lightning, for the laboratory air-fluorescence spectrum of Fig. 1, and for some nuclear-explosion-excited air-fluorescence spectra are given in Table II. Data are presented for two different bandwidths at 3914 Å: a 20-Å bandwidth is practical with the LASL-5, 5-in., five-element, quartz, 120° all-sky lens,[7] but a minimum bandwidth of 43 Å can be obtained at 3914 Å with the older LASL-2, 2-in., four-element, glass, 165° all-sky lens[7] which was used in the lightning study.[17]

In attempting to differentiate between the lightning spectrum and the "weak" air-fluorescence spectrum of Fig. 1, any of the discrimination channels would be effective. The ratios derived from the air-fluorescence spectrum are three times or more larger than the maximum observed ratios produced by lightning. Therefore, the discrimination system would not misidentify the source, and the only false triggering would be of the below-threshold type.

However, we must also consider the modified spectra of Table II as representative of possible air-fluorescence pulses excited by nuclear-explosion x rays. In general, the detection-channel to discrimination-channel ratios of these pulses are shifted toward the lower values of lightning. In many cases, there is considerable overlap of the distributions of lightning and air-fluorescence ratios. Therefore, a number of source-misidentification false triggers will be produced if discrimination channels are used in which overlap occurs.

In particular, at two of the discrimination channel wavelengths, the spectral-irradiance ratio produced by one of the nuclear-explosion air-fluorescence pulses (as underlined) is indistinguishable from that produced by lightning. At 4140 Å, lightning is indistinguishable from the spectrum derived from Bluegill; at 6563 Å, from Starfish. It is therefore impossible to construct a discrimination system based on spectral differences between 3914 and 4140 Å that would properly identify a Bluegill-like spectrum, or one using 3914 and 6563 Å that would properly identify Starfish.

At the other two discrimination-channel wavelengths, 4950 and 5000 Å, most air-fluorescence and lightning-pulse spectral-intensity ratios are discrete. For 4950-Å discrimination in conjunction with a 20-Å-wide 3914-Å detection channel, all air-fluorescence-pulse ratios are ≥ 6.5 and all lightning-pulse ratios are ≤ 4.5. Thus, a discrimination system that is free from source-misidentification false triggering can be realized. For 4950-Å discrimination in conjunction with the 43-Å-wide, 3914-Å detection channel of the 2-in.-lens system, and for 5000-Å discrimination for either detection system, a small degree of overlap exists between air-fluorescence and lightning-ratio distributions. This overlap will cause a fraction of the incident lightning signals to be misidentified if the discrimination system is adjusted to identify all the Table II air-fluorescence pulses correctly.

We will show later that the use of the 5-in. lens with 3914-Å detection and 4950-Å discrimination produces very few false triggers and so defines a highly effective lightning-discriminating detection system.

IV. DETECTOR SENSITIVITY*

The sensitivity of a radiometer is best described here by the minimum incident signals it can detect. For a monochromatic source such as the 3914-Å N_2^+ 1N (0,0) feature, the minimum-detectable signal must be expressed as an irradiance, h_m (W cm^{-2}). For continuum sources such as lightning at 3914, 4140, and 4950 Å, it must be expressed as a spectral irradiance, H_m (W cm^{-2} Å^{-1}). This latter term is also used to represent the minimum-detectable signal for a monochromatic plus continuum source, for which the signal is expressed as an average spectral irradiance over a given bandwidth. Examples of this type of source are the two lightning emissions at 5000 and 6563 Å.

In the presence of background radiation, with spectral radiance N_b (W cm^{-2} sr^{-1} Å^{-1}), the sensitivity of a radiometer is limited by the statistical fluctuations of the background-produced photoelectron beam of the photomultiplier. The photoelectron beam current, i.e., the cathode current, can be written

$$i_c = N_b \, \Omega \, A_e \, S \, T_o \, \Delta\lambda \ \text{(Amp)} \quad ,$$

where Ω is the solid angle (sr) subtended by the radiometer's field of view, A_e is the entrance pupil area (cm^2) of the radiometer, S is the sensitivity (Amp W^{-1}) of the photocathode, T_o is the transmittance of the lens and interference filter assembly at its peak wavelength, and $\Delta\lambda$ is the spectral bandwidth (Å) of the assembly. The rms noise current, i_n, present on this cathode current within the electrical bandwidth, Δf (Hz), of the amplifiers, is

$$i_n = \left(2 \, e \, \Delta f \, i_c\right)^{1/2} \quad \text{(Amp)} \quad ,$$

where e is the electron charge (Coul).

The minimum-detectable signal must produce a peak current, i_s, that is k times the noise current, i_n. The factor k is the signal-to-noise ratio and must be ~ 5 for reliable operation.

For a monochromatic source of minimum-detectable irradiance, h_m, we can write

$$i_s = k \, i_n = h_m \, A_e \, S \, T_o \ \text{(Amp)} \quad ,$$

or

$$h_m = k \left(\frac{2 \, e \, \Delta f \, N_b \, \Omega \, \Delta\lambda}{A_e \, S \, T_o} \right)^{1/2} \quad \text{(W cm}^{-2}\ \text{Å}^{-1}) \quad .$$

Thus, the minimum-detectable irradiance, h_m, becomes

*We follow Donahue's derivation of all-sky-detector sensitivity given in Reference 5; our nomenclature, however, is that endorsed recently by the Nomenclature Committee of the Optical Society of America.[6]

larger, i.e., the detector sensitivity decreases, for increases of electrical and spectral bandwidths and of solid angle and background radiance, and for decreases of entrance-pupil area, cathode sensitivity, and transmittance of the optics.

For a continuum source of minimum-detectable spectral irradiance, H_m, we find

$$i_s = k\, i_n = H_m A_e S T_o \Delta\lambda \text{ (Amp)} \quad ,$$

or

$$H_m = k \left(\frac{2\, e\, \Delta f\, N_b\, \Omega}{A_e S T_o \Delta\lambda} \right)^{1/2} \quad (\text{W cm}^{-2}\ \text{Å}^{-1}) \quad .$$

In this case, the detector becomes more sensitive as the spectral bandwidth increases; the dependence of sensitivity on all the other parameters remains as above.

We have used the parameter values given in Table III to derive detector sensitivities for this evaluation. The parameters given represent the best available and most suitable optical components at each wavelength. The daylight radiance, N_b, is conservatively assumed to be independent of wavelength. The actual decrease of N_b with increasing wavelength which occurs when the daylight sky is relatively clear enhances discrimination effectiveness, because all discrimination-channel background-light noise signals decrease relative to 3914 Å. The background radiance at night can be ~ 10^6 times smaller than during daylight, but it still remains the primary noise source in properly-designed radiometers.

The sensitivities of the 2- and 5-in. all-sky radiometers to the N_2^+ 1N (0,0) (3914-Å) radiation of air fluorescence are represented by the minimum-detectable irradiances at 3914 Å. From the appropriate parameters of Table III, we find that for daylight operation:

$$h_m \text{ (2-in.)} = 1.0 \times 10^{-7} \text{ W cm}^{-2} \quad ,$$

and

$$h_m \text{ (5-in.)} = 7.5 \times 10^{-8} \text{ W cm}^{-2} \quad .$$

These values of h_m are related to the maximum distance, R(km), from the earth at which a nominal nuclear explosion of x-ray yield Y_x (kilotons) can be detected. Bennett's calculations[18] can be used to infer the ground-level 3914-Å irradiance, h, from this nuclear explosion. If the efficiency of N_2^+ 1N (0,0) production is 0.5%[4] and the atmospheric transmission is 0.6,

$$h = \frac{300\, Y_x}{R^2} \quad (\text{W cm}^{-2}) \quad .$$

(For a 1-kt explosion at a distance of 10^3 km, the predicted 3914-Å irradiance is thus 3×10^{-4} W cm^{-2}.)

Table III. Radiometer-Sensitivity Parameters

Parameter	Lens: Two-Inch	Lens: Five-Inch	Units
Signal-to-noise ratio, k	5	5	
Electrical bandwidth, Δf	8	2	kHz
Solid angle*, Ω	4.3	2.65	sr
Entrance pupil area*, A_e	0.12	1.4	cm^2
Photocathode sensitivity, S_o			
3914 Å	0.060	0.060	Amp W^{-1}
4140 Å	0.065	0.065	" "
~ 5000 Å	0.053	0.053	" "
6563 Å	0.020	0.020	" "
Optics and filter transmission, T_o*			
3914 Å	0.17	0.16	
4140 Å	0.25	0.22	
~ 5000 Å	0.35	0.31	
6563 Å	0.36	0.32	
Spectral bandwidth, $\Delta\lambda$*			
3914 Å	43	20	Å
4140 Å	43	40	"
4950 Å	220	220	"
5000 Å	50	20	"
6563 Å	70	20	"
Spectral radiance of background, N_b			
day	10^{-6}	10^{-6}	W cm^{-2} sr^{-1} Å^{-1}
night	10^{-12}	10^{-12}	

*These data have been measured and are presented in Reference 7.

If the values of h_m given above are used in this expression, the system detection ranges, R, are:

$$R\ (2\text{-in.}) = 5.5 \times 10^4 \sqrt{Y_x}\ \ (\text{km})\quad ,$$

and

$$R\ (5\text{-in.}) = 2.0 \times 10^5 \sqrt{Y_x}\ \ (\text{km})\quad .$$

At night, the background spectral radiance decreases by a factor of $\sim 10^6$; the minimum-detectable irradiance decreases by a factor of $\sim 10^3$; and the nuclear-detection range increases by a factor of ~ 30. The maximum increase of sensitivity occurs on moonless nights.

In the derivations of false-triggering rates, we will need for each of the two detectors:

1. the minimum-detectable spectral irradiance, H_m, for a continuum source at 3914 Å, and

2. the minimum-detectable spectral irradiance for a continuum source at each of the discrimination wavelengths, relative to that at 3914 Å.

From the parameters of Table III, we find that the 3914-Å minimum detectable spectral irradiances for daylight operation are:

$$H_m\ (2\text{-in.}) = 2.5 \times 10^{-9}\ \text{W cm}^{-2}\ \text{Å}^{-1}\quad ,$$

and

$$H_m\ (5\text{-in.}) = 3.8 \times 10^{-10}\ \text{W cm}^{-2}\ \text{Å}^{-1}\quad .$$

At night, these values decrease by a factor of $\sim 10^3$.

To obtain the sensitivity of one detector at wavelength λ_1 relative to another at λ_0, we take the inverse of the ratio of their minimum-detectable spectral irradiances:

$$\frac{H_m(\lambda_0)}{H_m(\lambda_1)} = \left[\frac{S(\lambda_1)\,T_o(\lambda_1)\,\Delta\lambda(\lambda_1)}{S(\lambda_0)\,T_o(\lambda_0)\,\Delta\lambda(\lambda_0)}\right]^{1/2}\quad .$$

Detector sensitivities at the discrimination wavelengths, relative to $\lambda_0 = 3914$ Å, are given in Table IV. The values presented for the two lenses are normalized separately.

There is a strong increase of relative sensitivity with increasing bandwidth, as comparison of narrow and broad channels near 5000 Å shows. This increase is caused by the fact, discussed earlier, that the incident spectrum, which is a continuum, contains more energy in a broad bandwidth than in a narrow one.

Table IV. Sensitivities of Radiometers to Continuum Radiation Relative to 3914 Å

	Wavelength, Å				
	3914	4140	4950	5000	6563
			Two-Inch Lens		
Bandwidth, Å	43	43	220	50	70
Sensitivity	1.0	1.24	2.98	1.42	1.06
			Five-Inch Lens		
Bandwidth, Å	20	40	220	20	20
Sensitivity	1.0	1.75	4.37	1.32	0.83

There are line radiations, as well as a continuum, present in lightning emissions in some of the spectral channels shown in Table IV.[1] The relative sensitivities given assume, however, that the incident spectrum is a continuum or its equivalent, i.e., that contributions from line radiations are treated as if they were spread over the entire bandwidth of the radiometer. Thus, the strong H_α-line radiation at 6563 Å and the NII radiation at 5000 Å must be spread over broad bandwidths in the 2-in.-lens system and much narrower ones in the 5-in. system. The effects of the line radiations relative to the continuum radiations also present will thus be different in the two systems. We will use different source intensities for the two systems, at 5000 and 6563 Å, to express this difference. Radiation in the 4140-Å channel is primarily continuum and so is unaffected by differences of spectral bandwidth.

V. CALCULATION OF FALSE-TRIGGERING RATES

The evaluation of the four proposed discrimination channels for the detection system designs based on 2- and 5-in. lenses must include the effects of the following variables: detector parameters and background radiation which affect detector sensitivities, lightning emissions, air-fluorescence emissions, and atmospheric-transmission parameters. Early attempts to evaluate discrimination capabilities[1] indicated that it was necessary to consider all the variables and their variations simultaneously. We therefore developed a calculation to predict statistically, on the basis of all the variables, the number of false triggers of a detection system that would be produced by lightning if each of the discrimination channels were used. The calculation provides a means to compare accurately the lightning-discrimination capability of the various channels. In addition, it gives an estimate of the actual rates at which lightning will produce false triggers.

A. Variables that Affect the False-Triggering Rate

1. Detector Parameters. The only detector parameter we have not discussed is the discrimination ratio, i.e., that ratio of detection to discrimination-channel signals at which the source identification changes. If spectra similar to the air-fluorescence spectrum of Fig. 1 are to be differentiated from lightning spectra, a 3914-Å-to-discimination-channel ratio of 10 will effectively separate the two distributions of signals for each of the discrimination channels. Therefore, the primary calculations of false-triggering rates were based on this ratio of 10. The variations of false-triggering rates were also investigated as the ratio decreased from 10, to account for nuclear explosions that deposit large energy densities in the atmosphere.

2. Lightning Emissions. The emissions of lightning have been discussed in the first three volumes of this report.[1-3] We require, first, the distribution function of spectral intensities emitted at 3914 Å by lightning as determined from the collimated-detector data and presented in Volume II.[2] In summary, lightning emits 3914-Å spectral intensities of 3×10^{2} to 10^{7} W sr^{-1} Å^{-1}, with a most probable value of $\sim 10^{4}$ W sr^{-1} Å^{-1}.

We also require distribution functions of ratios of spectral intensity emitted by lightning at 3914 Å to spectral intensities in the discrimination-channel passbands. These functions have been derived as follows.

(a) 3914-Å/4140-Å ratio. For the 2-in.-lens system, the 3914-Å/4140-Å distribution function was generated from all-sky detector data. Wing has shown that the distribution of ratios is "log-normal," i.e., that the logarithms of the ratios have a "normal," Gaussian distribution. The average ratio is 1.2; the average deviation, ± 35%.[19]

For the 5-in.-lens system, we used the 3914-Å/4140-Å distribution function generated with collimated-detector results. Both collimated-detector bandwidths for this ratio were ~ 20 Å, and the distribution function is broader than that generated from the broader-band all-sky-detector data. This disparity of distributions is probably caused by the expected greater fluctuations of the lightning spectrum as the passband becomes narrower. We use the distribution function that will lead to the higher predicted false-triggering rate. Recently reduced results have been added to the data presented in Volume II,[2] giving an average 3914-Å/4140-Å ratio of 1.05 ± 40%.

(b) 3914-Å/4950-Å ratio. For both systems, the 3914-Å/4950-Å distribution function was generated from a relatively poor sample of all-sky-detector data, recorded by Amato with a 4915-Å, 174-Å-bandwidth, 2-in.-lens detector.[17] The distribution used is "log-normal," with an average ratio[19] of 1.2 ± 36%.* To be conservative, we have added uncertainty to the distribution by using an average deviation twice that given by the data. Amato also used a similar radiometer centered at 4870 Å during the 1963 lightning study.[6] Considering the effects of an apparent sensitivity change of that detector during daylight, his 1963 results and the 1965 average ratios used here are in excellent agreement.

(c) 3914-Å/5000-Å ratio. No narrow-passband radiometers were operated at 5000 Å during any of the lightning studies because the possible value of this spectral feature for discrimination was first recognized by Connor during the analysis of the slitless spectra taken in 1965.[1] The present treatment is an extension of his discussion of discrimination in the context of a more quantitative calculation. Our lack of detailed knowledge

*For this sample, to be conservative, we have used storm-44 data which were rejected in the presentation of Volume III. They represent a substantial fraction of the 1965 data sample, and modify the ratio distribution so as to increase the predicted false triggering rate.

of the variability of the 3914-Å/5000-Å ratio, however, has forced us to be conservative in our estimate of the distribution function, and so we may underestimate the effectiveness of 5000 Å for discrimination. Our false triggering rates for 5000-Å discrimination therefore approximate an upper limit to those that would be predicted with proper input data.

Connor has generated average ratios and their distribution functions from 50 return-stroke slit[20] and slitless[1] spectra. For 20-Å-wide spectral channels, representative of the 5-in.-lens system,[7] he finds the 3914-Å/5000-Å ratio to be 0.5 ± 25%. We have used, instead, a log-normal distribution with an average ratio of 0.67 and an average deviation of ± 40%. The average ratio was increased to 0.67 because other types of lightning phenomena, such as cloud pulses, are not represented among the spectrograph data. These phenomena are probably weaker pulses and may have a lower degree of ionization than return strokes. If so, the 5000-Å NII feature would be considerably weaker, relative to 3914 Å, than the return-stroke average. We substantiate this argument as follows. Continuing currents are weak phenomena for which spectra were obtained; they show weaker NII 5000-Å radiation than do higher-current return strokes.[1] We feel that the ratio of 0.67 is a conservative average of 3914-Å/5000-Å ratios for 20-Å bandwidths from a data sample including all lightning phenomena. The average deviation of ± 40% of the average ratio is typical of average deviations derived from the collimated-detector data for other wavelengths and 20-Å bandwidths.

For a 50-Å-wide channel at 5000 Å and a 43-Å-wide channel at 3914 Å, representative of a 2-in.-lens system,[7] the 5000-Å line contribution must be reduced, thereby increasing the 3914-Å/5000-Å ratio. The continuum level at this point on the spectrum is known, relative to 3914 Å, from the 3914-Å/4915-Å data discussed above. We have used an average 3914-Å/5000-Å ratio of 1.0 ± 40%, where the average deviation is again 40%.

(d) 3914-Å/6563-Å ratio. For the 20-Å-width channels of the 5-in.-lens system, we have used the distribution function derived from collimated-detector data and presented in Volume II.[2] The average 3914-Å/6563-Å ratio is 0.47, its average deviation is ± 40%.

For the 70-Å-wide 6563-Å channel of the 2-in.-lens system,[7] the 6563-Å Hα line contribution is smaller than that for a 20-Å-wide channel. The 3914-Å/6563-Å ratio derived from the all-sky-detector lightning results cannot be used, owing to a filter imperfection.[3] We have used a conservative average 3914-Å/6563-Å ratio of 0.83 ± 40% with a "log-normal" distribution.

3. Atmospheric Transmission. To predict false-triggering rates of an all-sky detection system, we must know how the spectral irradiance, H, at the detector depends on the spectral intensity, I, emitted by lightning as a function of distance, x, and wavelength, λ. We have presented this subject in Volume III[3] of this series; the conclusions are summarized below.

Five factors influence the distance dependence of signals detected by an all-sky radiometer at any wavelength.

(a) The inverse-square law decreases the detected irradiance with increasing distance by a factor of x^{-2}.

(b) Atmospheric scattering and losses through the top and bottom of the atmosphere decrease the detected irradiance approximately exponentially with distance by a factor of $\exp(-\mu_{eff}x)$, where μ_{eff} is an effective extinction coefficient (km^{-1}).

(c) The final scattering into the all-sky detector's entrance pupil is proportional in strength to the scattering coefficient, μ_s (km^{-1}), above the detector, in the absence of clouds.

(d) Clouds above the all-sky detectors can add strong scattered signals, relative to atmospheric volume scattering. We have used a variable factor to account for (c) and (d), as discussed below.

(e) The measured irradiance depends on the all-sky detector's field of view by a factor of g which represents the fraction of incident scattered light collected. Thus, for a "spherical," uniformly responsive detector, g = 1.

The distance dependence of the spectrum detected by an all-sky detection system, relative to 3914 Å, is not affected by the inverse-square law, which operates equally at all wavelengths. If all the detectors are of the same type, their field-of-view factors are also equal. The modifications of the relative spectrum are thus caused only by atmospheric scattering and lie between the following extremes.

In a dense atmosphere with visibility of 25 km or less, the detected relative spectrum does not differ from the emitted spectrum, to a good approximation.

In a clear atmosphere in which the visibility is ~ 100 km or greater, the relative spectrum may be modified as follows. For source-to-detector distances of 40 km or less, the spectrum recorded by an all-sky detector of 120° or 165° field of view is stronger in the blue than the source spectrum because blue light scatters more strongly into the detector's entrance pupil than does red light. This enhancement can be as much as a factor of 2 for 3914 vs 6563 Å. For distances of 60 km or greater the red end of the spectrum is enhanced (by as much as a factor of 3 at 100 km) at 6563 Å relative to 3914 Å. This red enhancement is caused by a loss of blue light, by scattering, over the long path to the detector. The change from blue to red enhancement occurs, and the detected spectrum is the same as the source spectrum, at about 50 km.

Clouds over the shorter source-to-detector scattering paths minimize the blue enhancement of the relative spectrum owing to the large contribution at all wavelengths of light scattered at the lower cloud surface. The red enhancement at larger distances may occur with clouds over the detector if most of the light-propagation path is through a clear atmosphere.

We have derived the following values of the parameters μ_{eff} and g for all-sky detectors.

(a) The effective extinction coefficient, μ_{eff}, is invariably less than the atmospheric extinction coefficient, μ. Thus, the all-sky detector signals at all wavelengths decrease more slowly with increasing distance than the direct-path distance dependence of $\exp(-\mu x)$, owing to the stronger scattered light incident from sources at greater distances.

The relationship between μ_{eff} and μ cannot be derived precisely from available data. We know from preliminary calculations that μ_{eff} varies from ~ 0.5 μ for μ = 0.03 km^{-1} (> 100-km visibility) to ~ 0.25 μ for μ = 0.2 km^{-1} (20-km visibility). We infer from the lack of distance dependence of the relative spectrum for dense atmospheres that μ_{eff} is approximately independent of wavelength for μ > 0.15 km^{-1}.

(b) The field-of-view factor, g, is approximately equal to $\Omega/2\pi$, where Ω is the solid angle subtended by the detector's field of view.

At 3914 Å, the relation between the emitted spectral intensity I (W sr^{-1} Å^{-1}) and the detected irradiance H(x) (W cm^{-2} Å^{-1}) at distance x (km) in the absence of clouds is approximately

$$H(x) \cong 10^{10}\, I\, \frac{\Omega}{2\pi} \left(e^{-\mu_{eff} x}/x^2 \right) .$$

The factor of 10^{10} is required by the different units of H and x.

To account approximately for the variation from a clear, cloudless atmosphere through a denser, clouded one, we have multiplied H(x) by a factor, k, which varies from 0.5 to 2. The smaller values represent a clear atmosphere in which H(x) is proportional to μ_s. The larger values are valid when clouds are present over the detector.

B. Calculation Method

The false-triggering rate for a given pair of detectors under given atmospheric conditions is calculated as follows.

1. A lightning pulse is assumed to occur at a distance, x, from the detector.

2. A small range of 3914-Å spectral intensities, say, I to I + ΔI, is assumed for this pulse. I must fall between 3×10^2 and 10^7 W sr^{-1} Å^{-1}, where lightning is known to radiate.[2] The probability, ΔF(I), that the spectral intensity is between I and I + ΔI is given by the distribution function[2]

$$\Delta F(I) = [dF/d(\log I)]\, \Delta I/I .$$

3. This pulse can be detected by the 3914-Å detector if its intensity, I, produces a spectral irradiance, H, at the detector that is larger than its minimum-detectable spectral irradiance, H_m. H

is calculated from I and the propagation mechanisms and is compared with H_m.

4. If the pulse can be detected at 3914 Å, it can also produce a false trigger. Whether it does so depends on the relative strength of the discrimination-channel spectral intensity.

(a) If the discrimination-channel spectral intensity radiated is so low that the signal at the detector is below its minimum-detectable spectral irradiance, H_m', a "below-threshold" false trigger occurs. The limiting discrimination-channel spectral intensity, I_m', can be calculated from H_m' and propagation mechanisms, and the ratio $R_m = I/I_m'$ can be formed.

(b) If the discrimination-channel spectral intensity radiated is so low that the ratio of 3914-Å to discrimination-channel spectral irradiances at the detector is greater than the discrimination ratio, R_c, that defines lightning vs air-fluorescence identification, a source misidentification false trigger occurs. The limiting spectral-intensity ratio, R_s, at the source can be calculated from R_c and propagation mechanisms.

5. If the pulse has a 3914-Å to discrimination-channel spectral intensity ratio greater than either R_m or R_s, a false trigger of one type or the other occurs. The probability of this false trigger is the product of a) the probability that the pulse has a 3914-Å spectral irradiance in the interval $(I, I + \Delta I)$, and b) the probability that the ratio is greater than either R_m or R_s, which can be obtained from the appropriate spectral-intensity-ratio distribution function.

6. The calculation, at distance, x, is performed for all values of I radiated by lightning. The probabilities are summed. This calculation gives for a stroke that occurs a horizontal distance, x, from the detectors the probability that it can be detected at 3914 Å and the probability that it will produce a false trigger.

7. The calculation is repeated for all distances, x, from 1 km to a distance so great that no lightning pulse can be detected. The results at each distance are weighted as though one lightning stroke occurs on every square kilometer, and they are summed for all distances.

8. The calculation outputs are a) the number of pulses detected at 3914 Å, and b) the number of false triggers received, assuming that, on the average, one lightning stroke has occurred on every square kilometer near the detection station. Also retained in the calculation outputs is c) the dependence of each of the probabilities on distance, x.

9. The false-triggering rates per storm can be estimated by assigning $\sim 10^4$ pulse to each storm. This value represents an active storm of 500 flashes with an average of 20 pulses each. As an example, for a given set of conditions, if lightning can be detected to a maximum distance of 56 km, the number of pulses assumed by the calculation at the rate of one per square kilometer would be $\sim 1 \times 10^4$, representing one storm spread uniformly throughout the 56-km radius.

C. Results

We first present predicted false-triggering rates for typical daylight and night conditions. These results are adequate for evaluating the relative merits of the four discrimination channels for a given detection-system design and for comparing the two designs. We then discuss to what extent the relative evaluation and the predicted false-triggering rates depend on input parameters, and so define the errors of the evaluation method.

1. Typical Conditions. Our primary calculations have been made under the following atmospheric conditions. The effective extinction coefficient was 0.080 km^{-1} which represents a relatively dense atmosphere at Los Alamos altitude but a typical one at sea level. The factor, g, (see Part A 3) was 0.6 for the 165°, 2-in.-lens system and 0.3 for the 120°, 5-in.-lens system. The cloud factor, k, was assumed to be 1.0. The relative spectrum detected by the two detection systems was assumed to be independent of distance. These inputs represent typical atmospheric conditions as derived from data of the 1965 lightning study.[3]

The primary results are based on the use of a discrimination ratio of 10 as the division between air fluorescence (higher ratios) and lightning. With this value, all false triggering is caused by below-threshold signals incident at the discrimination wavelength.

Table V. False Triggers Caused by One Lightning Pulse per Square Kilometer

System Lens	Time	Nuclear Detection Range, km	Lightning Detection Range, km	Pulses Detected at 3914 Å	False Triggers			
					4140 Å	4950 Å	5000 Å	6563 Å
Two-inch	Day	$5.5 \times 10^4 \sqrt{Y_x}$	46	500	38	0.19	$\lesssim 14$	23
	Night	$1.7 \times 10^6 \sqrt{Y_x}$	110	10,300	400	1.9	$\lesssim 140$	240
Five-inch	Day	$2.0 \times 10^5 \sqrt{Y_x}$	60	1250	28	0.01	$\lesssim 6$	22
	Night	$6.0 \times 10^6 \sqrt{Y_x}$	128	16,000	190	0.05	$\lesssim 38$	145

The outputs of the calculation for these atmospheric conditions are given in Table V, assuming one pulse per square kilometer. This calculation predicts fractional false triggers, owing to the way the probabilities are computed.

(a) Two-inch-lens system, daylight. Of the 6650 pulses produced within the lightning detection range of 46 km, 500 are detected by the 3914-Å detector. This small fraction is a consequence of the rapid decrease of the probability that an emitted pulse can be detected as the source-to-detector distance increases. About seven percent of the pulses detected produce false triggering if 4140 Å is used for discrimination. This rate is larger than that predicted by the 1963 analysis[6] because of the incorporation of below-threshold false triggering. The 6563- and 5000-Å channels are factors of 1.6 and > 2.7 better for discrimination than 4140 Å, respectively. The 220-Å-wide channel at 4950 Å is ~ 200 times better than 4140 Å for discrimination. The improvement represents the decrease of below-threshold false triggering when a broad, continuum-sensing discrimination channel replaces a narrower one.

(b) Two-inch-lens system, night. At night the nuclear-explosion detection range increases ~ 30 times; the number of lightning pulses detected at 3914 Å increases ~ 20 times; and false triggers increase ~ 10 times.

(c) Five-inch-lens system, daylight. The 5-in. system has ~ 3.5 times greater nuclear-explosion daylight detection range than the 2-in. system and it detects 2.5 times as many lightning pulses at 3914 Å. However, there is less false triggering. These characteristics are caused by the larger entrance pupil and narrower 3914-Å passband of the 5-in. lens[7] which increase the sensitivity to the narrow bandwidth N_2^+ (0,0) (3914-Å) emission of air fluorescence but decrease sensitivity to the lightning continuum. There is a factor of $\gtrsim 4$ decrease in false triggering relative to 4140 and 6563 Å if a 20-Å band at 5000 Å is used for the discrimination channel. This substantiates Connor's preliminary conclusion of Volume I.[1] However, there is a much larger improvement of discrimination capability with the 220-Å-bandwidth channel at 4950 Å: false triggering is ~ 3000 times less than with 4140-Å discrimination. We limit the predictions at 4950 Å for the 5-in. system to order-of-magnitude estimates, as will be discussed later.

(d) Five-inch-lens system, night. At night, the nuclear-explosion-detection range, the number of pulses detected at 3914 Å, and the number of false triggers increase by factors of ~ 30, ~ 13, and ~ 6, respectively.

2. Estimate of Actual False-Triggering Rates. The actual rates at which false triggers will be received can be estimated by multiplying the calculation results for typical atmospheric conditions, which assume one lightning pulse per square kilometer, by an estimate of the actual number of pulses per detected storm that fall on that square kilometer.

The maximum distance from which lightning can be detected in daylight is ~ 60 km for the 5-in. system. The area within this "detection range" circle is 1.13×10^4 km^2. Thus, the rate of 1 pulse/km^2 used in the calculation is approximately equivalent to one active storm averaged in its effect over the

Table VI. Yearly False-Triggering Rates of Detection Systems

System Lens	Time	Nominal Detection Range, km	Pulses Detected at 3914 Å	False Triggers			
				4140 Å	4950 Å	5000 Å	6563 Å
Two-inch	Day	$5.5 \times 10^4 \sqrt{Y_x}$	5000	380	1.9	< 140	230
	Night	$1.7 \times 10^6 \sqrt{Y_x}$	20,600	800	3.8	< 280	480
	Total	--	25,600	1180	5.7	< 420	710
Five-inch	Day	$2.0 \times 10^5 \sqrt{Y_x}$	12,500	280	0.1	< 60	220
	Night	$6.0 \times 10^6 \sqrt{Y_x}$	32,000	380	0.1	< 76	290
	Total	--	44,500	660	0.2	< 136	510

entire area within daylight detection range of the detection station. The number of false triggers given for daylight sensitivies is, therefore, without correction, the average number of false triggers per daylight storm.

At night the detection range increases to 128 km for the 5-in. system, an area of ~ 5×10^4 km^2. The assumed rate of 1 pulse/km^2 produces a total number of pulses equivalent to five active storms. Thus, the numbers of pulses given in Table V for night storms should be multiplied by 0.2 to give the per-storm false-triggering rate.

Let us consider a detection station at a site that records an average of 20 daylight storms within detection range per year. Storms vary in activity, and we assume that these 20 storms are equivalent to 10 active storms that produce 10^4 pulses each. This storm rate is roughly equivalent to one-half the rate recorded at Los Alamos, where the thunderstorm activity is higher than the average for the rest of the country.[21]

Malan shows that the probability per unit area of a night storm is ~ 0.2 times the daylight probability.[22] However, the area over which lightning can be detected is ~ 5 times larger at night than in daylight. Therefore, approximately equal numbers of storms are recorded during day and night.

The false triggers per year at our hypothetical detection site under typical conditions are given in Table VI. For 4140- and 6563-Å discrimination there are ~ 10^3 false triggers per year. An improvement of a factor of $\gtrsim 4$, to < 100 to 400 false triggers per year, can be realized by use of 5000 Å for discrimination. However, the 4950-Å discrimination channel will pass ~ 6 false triggers of a 2-in. system per year and approximately one false trigger of a 5-in. system per 5 years.

3. Dependence of Predictions on Parameters

(a) Effective extinction coefficient, μ. We have made false-triggering rate predictions for effective extinction coefficients, μ, of 0.040, 0.080, 0.120, 0.20, and 0.40 km^{-1}, assuming that the extinction coefficients are independent of wavelength. The numbers of pulses detected at 3914 Å, and the numbers of false triggers given above for $\mu = 0.080$ km^{-1}, must be multiplied by a factor of ~ 2 for $\mu = 0.040$ km^{-1} and by a factor of ~ 0.6 for $\mu = 0.120$ km^{-1}. These results are typical of atmospheric conditions for storms farther than 10 km from the detectors. When the storm passes over the detector position, extinction coefficients of 0.20 and 0.40 km^{-1} can be applicable. For these cases, the numbers of pulses detected at 3914 Å with $\mu = 0.080$ km^{-1} decrease by factors of 3 and 8, respectively, and the numbers of false triggers predicted decrease by approximately the same factors.

The relative numbers of false triggers, for the two systems, change by less than 30% as the effective extinction coefficient changes from 0.040 to 0.40 km^{-1}.

(b) Cloud factor, k. The cloud factor, k, has been varied in the calculations of false-triggering rates to account for variations of scattering mechanisms under different atmospheric conditions. Larger k-values mean that the system is more sensitive to lightning, so that more pulses are detected at 3914 Å and more false triggering occurs. Over the range $0.5 \le k \le 2$, the numbers of pulses detected at 3914 Å and the numbers of predicted false triggers vary by ± 40%. The relative rates at which false triggering occurs when two discrimination channels or systems are compared are independent of k.

(c) Wavelength dependence of μ. As noted, the spectrum of lightning from a storm in an otherwise clear atmosphere can be modified in its propagation to the detectors. In a clear atmosphere, the numbers of pulses detected at 3914 Å by both detection systems, and the false triggering rates of all 2-in.-lens discrimination channels, are about twice those in the denser atmosphere. False triggering of the 5-in. system increases by a factor of ~ 2 at 4140 Å and a factor of 1.6 at 6563 Å, and is relatively unaffected at 4950 and 5800 Å.

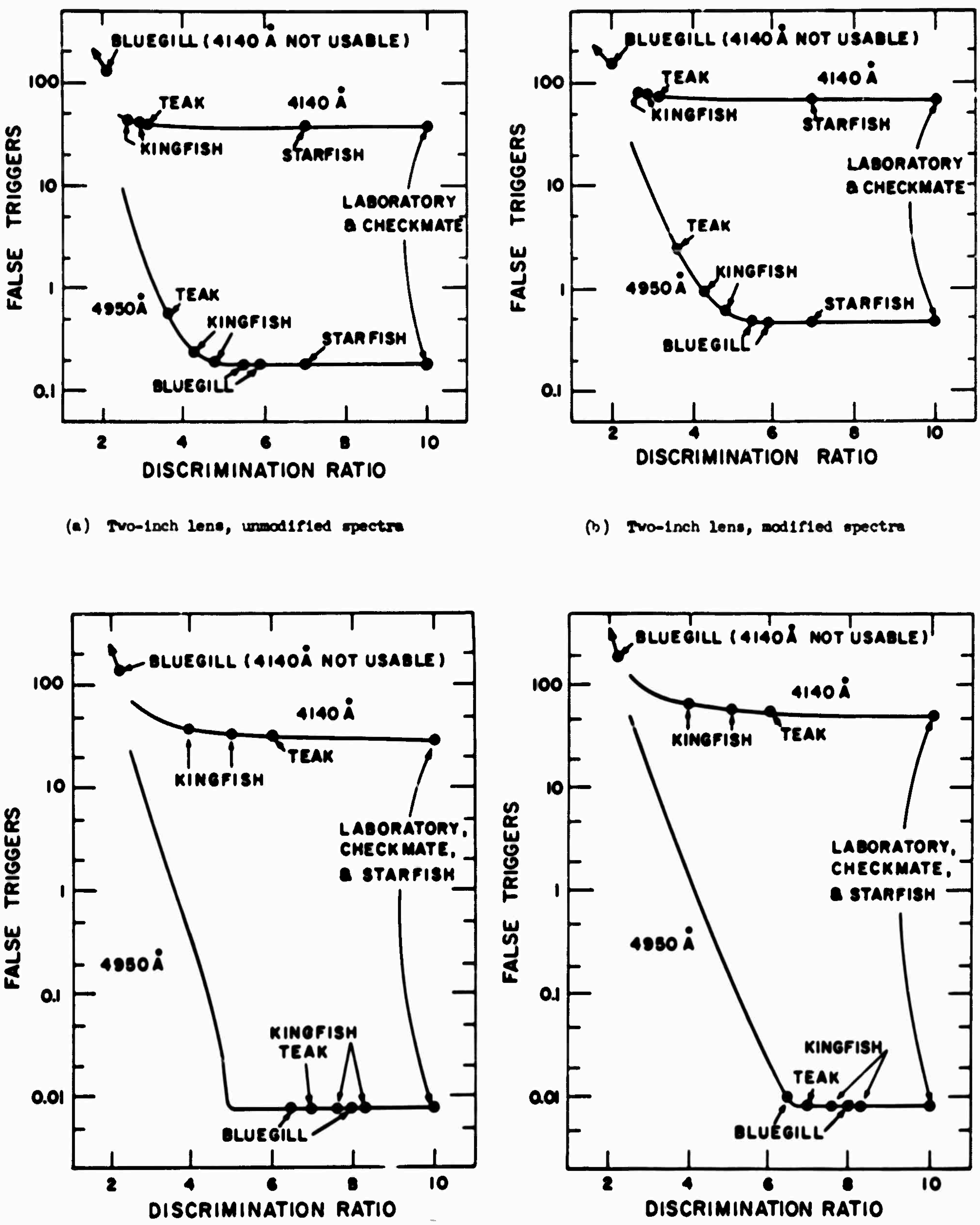
(d) Discrimination ratio. The previous results have been derived under the assumption that differentiation between lightning and laboratory air-fluorescence spectra was required. However, we have shown that nuclear-explosion-excited air-fluorescence spectra can differ from the laboratory spectrum, particularly in the N_2^+ 1N (0,0), 3914-Å, feature, when the energy deposited in the atmosphere is large. The discrimination system can identify these spectra properly only if the discrimination ratios are reduced from the value of 10 assumed in the previous calculations. When lower values of the discrimination ratio are required, source-misidentification false triggering may be produced.

To investigate the effects of reduced discrimination ratios, we have made false-triggering-rate calculations in which the discrimination ratio was varied as a parameter. The calculations were made for two atmospheric conditions: typical, dense atmosphere and a clearer atmosphere. Results for 4140- and 4950-Å discrimination are shown in Fig. 2; (a) and (b) give results for the 2-in.-lens system in typical and clear atmospheres, respectively, and (c) and (d) give similar results for the 5-in.-lens system.

In the dense atmosphere, source misidentifications begin to increase the false-triggering rate as the discrimination ratio becomes < 5. For 4140-Å discrimination, a discrimination ratio of 2.5 with the 2-in. system, and 3.3 with the 5-in. system correctly identifies all-air-fluorescence-pulse spectra except those derived from Bluegill, with less than a factor of 2 increase of the false triggering rate relative to below-threshold false triggering. The Bluegill-derived spectra cannot be identified properly by an effective discrimination system based on 4140 Å.

For 4950-Å discrimination, a discrimination ratio of 3.5 for the 2-in. system correctly identifies all air-fluorescence pulses, and, although the false-triggering rate is increased a factor of ~ 3 relative to below-threshold false triggering, 4950-Å remains significantly better than other wavelengths for discrimination. The increase in the false triggering rate of the 5-in. system from source misidentifications occurs for a discrimination ratio that is significantly lower than any produced by air-fluorescence pulses. Therefore, a discrimination ratio of 6 correctly identifies all air-fluorescence sources and does not increase the false-triggering rate.

If atmospheric scattering causes a blue enhancement of the lightning spectrum, as may occur in clear atmospheres,[3] the discrimination systems are more subject to source-misidentification false triggering because the blue enhancement effectively shifts the lightning spectral intensity ratios toward the ratios of air-fluorescence pulses. Figures 2(b) and (d) represent a clearer atmosphere than do (a) and (c), with a blue enhancement and distance dependence of the lightning spectrum as discussed earlier. Because the atmosphere is clearer, and lightning can be detected from larger distances, the below-threshold false-triggering rates of (b) and (d) differ from those of (a) and (c). The increases of false-triggering rates due to source misidentifications show the same qualitative behavior as those for the unmodified spectrum. For both lens systems, 4140-Å false triggering increases by a factor of < 2 by source misidentifications, owing to the high below-threshold false-triggering rates. With 4950-Å discrimination, the 2-in. system



(a) Two-inch lens, unmodified spectra

(b) Two-inch lens, modified spectra

(c) Five-inch lens, unmodified spectra

(d) Five-inch lens, modified spectra

Fig. 2. Dependence of predicted numbers of false triggers on discrimination ratio.

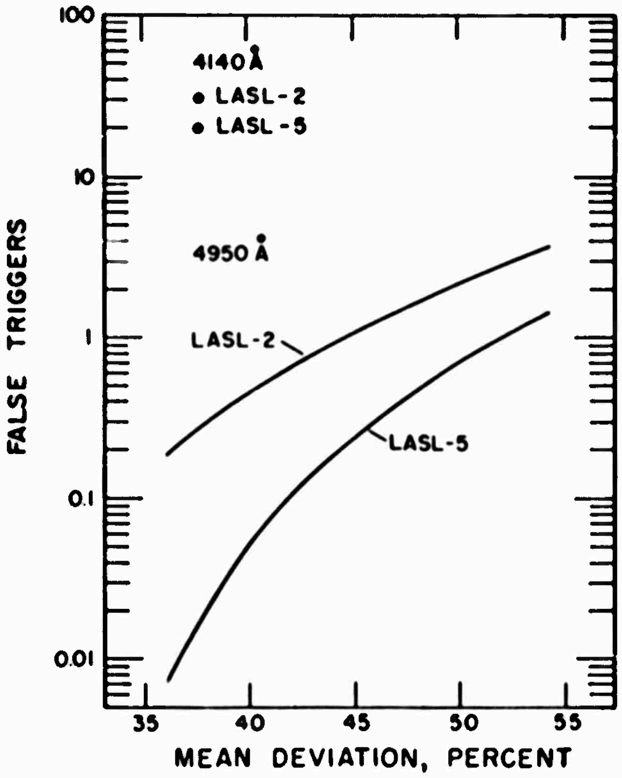


Fig. 3. Dependence of false-triggering rate on mean deviation of the 3914-Å/4950-Å distribution.

false-triggering rate increases by a factor of 5 but remains significantly better than that for other channels. The 5-in. system with a 4950-Å discrimination ratio of ~ 6 is not affected significantly by source-misidentification false triggering, and can properly identify all the air-fluorescence pulses.

False-triggering rates with 5000- and 6563-Å discrimination behave similarly to the 4140-Å rate as the discrimination ratio is decreased. The below-threshold false triggering rates of these systems are large enough that source-misidentification false triggering is relatively unimportant throughout the range of air-fluorescence pulse ratios, except for the specific case of Starfish for which effective discrimination with 6563 Å is impossible.

(e) 3914-Å/4950-Å distribution function. The predictions of false-triggering rates for 4950-Å discrimination are at the limit of accuracy of the calculations. These results are strongly influenced by the shape of the spectral-intensity-ratio distribution function for large values of the 3914-Å/4950-Å ratio. As we noted earlier, the data sample leading to this distribution function was limited. Therefore, the predictions should be considered as an order-of-magnitude estimate of the false triggering produced when 4950 Å is used for discrimination.

To evaluate the effect of variations in width of the distribution function, we have predicted false-triggering rates if the mean deviation of the 3914-Å/4950-Å ratio distribution increases beyond 36%, as shown in Fig. 3. The 5-in.-lens system is particularly sensitive to increases of the mean deviation; the false-triggering prediction increases by a factor of almost 10 for a mean-deviation change from 36% to 40%. The discrimination capability remains substantially better than that of any other channel even for a mean deviation as large as 50%, although we feel that a mean deviation larger than 40% is extremely improbable. As we have noted, the mean deviation of 36% already represents a doubling of the distribution width given by the data.

(f) 4950-Å bandwidth. To obtain maximum discrimination effectiveness when a continuum channel is used, the largest possible spectral bandwidth should be employed. We have derived the bandwidth of 220 Å at 4950 Å as the broadest band that can be fit between maxima of the air-fluorescence spectrum. However, in practice, it may be difficult to obtain satisfactory behavior of a radiometer that is subjected to the large background flux contained within a 220-Å bandwidth.[18] It may thus be necessary to limit the bandwidth to less than 220 Å. This limitation would affect the detector sensitivity and, therefore, the false-triggering rate.

We have calculated the numbers of false triggers for 4950-Å bandwidths of from 220 to 100 Å, as shown in Fig. 4. Within this range, and particularly for bandwidths ≥ 130 Å, the discrimination efficiency of 4950 Å remains substantially better than that for other channels.

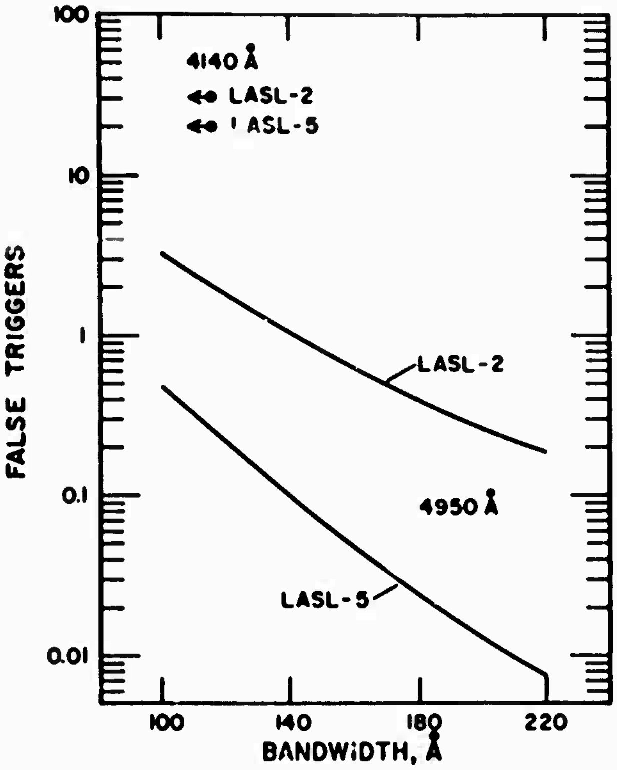


Fig. 4. Dependence of false-triggering rate on 4950-Å bandwidth.

VI. DISCRIMINATION OF A LARGE AREA, SOLID-STATE AIR-FLUORESCENCE DETECTION SYSTEM (SSAFDS)

Recent studies have shown that a large, broad-band array of infrared-sensitive, solid-state detectors can detect nuclear explosions at distances about 10 times greater than can the radiometer systems. The detection medium is fluorescence in the upper atmosphere of the entire first positive group of N_2. These systems are also extremely sensitive to lightning.

We have investigated self-discrimination of a solid-state array by means of spectral isolation into two bands within the infrared and comparison of the signals in these bands. As Donahue has shown,[5] spectral differences between air-fluorescence and lightning pulses become smaller as the spectral regions in which differences are to be measured become broader. We have considered infrared spectral regions as narrow as 200 Å and have found no suitable combination of wavelengths that would permit effective lightning discrimination. In particular, the combination of 200-Å-wide channels at 8900 Å [N_2 1P (1,0)] for detection and 8200 Å [NI (2)] or 7450 Å [NI (3)] for discrimination would be effective only under certain selected circumstances.

We have also studied discrimination of a solid-state array by an auxiliary pair of photomultiplier-tube radiometers, based on 5-in. all-sky lenses at 3914 Å (20-Å bandwidth) and 4950 Å (220-Å bandwidth). This "discrimination system" has been shown in previous sections to be extremely effective for discrimination, and it also has a sensitive detection capability of its own. However, the discrimination capability of the hybrid system including the solid-state array is poor because the discrimination radiometers are limited in sensitivity relative to the solid-state detector. This disparity in sensitivities permits a high rate of false triggering when weak lightning pulses detected by the main array are below the thresholds of the discrimination radiometers.

The false-triggering rate of such a hybrid system can be decreased by decreasing the sensitivity of the solid-state array to approximately the sensitivity of the discrimination channels during periods of lightning activity. This would, of course, produce a corresponding reduction in nuclear detection range.

We therefore recommend that a 5-in.-lens discrimination system be designed for the proposed solid-state detection systems. The operating procedure of such a hybrid system would include the limitation of the main array sensitivity for the duration of an electrical storm. The "discrimination system" would, itself, have a nuclear-detection range of $2 \times 10^3 \sqrt{Y_x}$ km, effectively lightning discriminated, regardless of the main-array sensitivity. Also, because of the high degree of spectral resolution made available by the 5-in. lens through the visible, other information can be obtained.

VII. SUMMARY AND RECOMMENDATIONS

We have considered the prevention of false triggering by lightning of nuclear-explosion detection systems sensitive to N_2^+ 1N (0,0) (3914-Å) fluorescence. Lightning discrimination based on recognition of the source spectrum is effective against a large fraction of the detected pulses if a spectral region near 4140 Å (40-Å bandwidth), 4950 Å (220-Å bandwidth), 5000 Å (20-Å bandwidth), or 6563 Å (20-Å bandwidth) is used as a discrimination channel. We have evaluated each discrimination channel quantitatively on the basis of experimental and theoretical evaluations of false triggering. Detection systems that use either the 2-in.-diam "LASL-2" or the improved 5-in.-diam "LASL-5" all-sky lens were analyzed.

For LASL-2-lens radiometers, 4140 Å is the poorest discrimination channel but is still effective against ~ 95% of all lightning pulses detected. The actual false-triggering rate is ~ 10^3 per year. Discrimination with 6563 Å gives ~ 40% improvement in the false-triggering rate. The improvement using 5000 Å is at least a factor of 2.8, relative to 4140 Å, and may be significantly more. A great improvement is obtained with a 220-Å-wide channel at 4950 Å, which, under typical conditions, permits only about six false triggers per year.

If the LASL-2 radiometers are replaced by a LASL-5 system, the nuclear-explosion detection range increases by a factor of ~ 3.5; and the number of lightning pulses detected per year increases by a factor of 1.7, but the number of false triggers decreases. This improvement is caused by the increased sensitivity to N_2^+ 1N (0,0) (3914-Å) radiation of air fluorescence and the decreased sensitivity to the 3914-Å continuum of lightning of the narrower spectral passband of the LASL-5 lens at 3914 Å. Discrimination-channel effectiveness increases in the same order as that given for the LASL-2 system: 4140-Å discrimination is effective against 98.5% of the detected pulses and about 660 false triggers occur; 6563 Å produces a small improvement; and 5000 Å is at least a factor of 4.8 better than 4140 Å.

The combination of a 220-Å-wide 4950-Å discrimination channel and a LASL-5 detection system nearly eliminates false triggering. Although the calculated rate of one false trigger per five years (equivalent to 5 x 10^{-8} of the detected pulses) is an order-of-magnitude estimate, in any case, the value of this channel and system for discrimination is unsurpassed.

We therefore recommend that new detection systems be equipped with LASL-5 radiometers, and that discrimination against lightning be accomplished with a 220-Å band centered at 4950 Å. A pair of LASL-5 radiometers, centered at 3914 Å (20-Å bandwidth) and 4950 Å (200-Å bandwidth) is the most effective discrimination system for the solid-state air-fluorescence detection system that we can recommend at present.

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